Increasing soil organic carbon sequestration and yield stability simultaneously through combined no-tillage and straw return in wheat-maize rotation

Jianglan Shi[1], Shuo Li[2], Xiushuang Li[2], and Xiaohong Tian[3]

[1]Northwest A&F University
[2]Northwest Agriculture and Forestry University
[3]Northwest Agriculture and Forestry University College of Resources and Environment

July 9, 2021

Abstract

Knowledge about the changes in soil organic carbon (SOC) stocks and grain yields under different tillage and straw management is necessary to assess the feasibility and sustainability of conservation agriculture. An 8-year experiment was conducted in an intensive wheat (Triticum aestivum L.)–maize (Zea mays L.) rotation system in the southern Loess Plateau of China. Three tillage methods [control with no-tillage and straw removal (CK), no-tillage with straw stubbles 30–40 cm in height (NT), and rotary tillage with straw incorporation (RT)] were applied before maize planting, and two straw treatments [straw return (SR) and no straw return (SR0)] were applied after maize harvest. Thus, the treatments included CK-SR, CK-SR0, NT-SR, NT-SR0, RT-SR, and RT-SR0. Over 8 years, the SOC stock exhibited similar dynamic trends in all treatments, but was higher in NT, RT, and SR plots than in CK-SR0 plots. Compared with the initial soil, the SOC stock increased largest (34.1%) in NT-SR. Compared with the CK-SR0, the NT-SR, RT-SR, CK-SR, NT-SR0 and RT-SR0 increased the wheat grain yield by 47.2%, 36.8%, 24.9%, 25.1%, and 20.0%, respectively. The NT, RT and SR increased crop yield stability with the highest sustainable yield index in NT-SR for both wheat (0.67) and maize (0.70). This study showed the NT-SR was the best strategy for improving SOC stocks, grain yields and agricultural sustainability for the wheat-maize rotation system in northwestern China and other areas with similar climates and cropping systems.

Title:

Increasing soil organic carbon sequestration and yield stability simultaneouslythrough combined no-tillage and straw return in wheat-maize rotation

Jianglan Shi #| Shuo Li #|Xiushuang Li| Xiaohong Tian

College of Natural Resources and Environment, Northwest Agriculture and Forestry University, Yangling, Shaanxi, 712100, China

# These authors contributed equally to the work as the co-first authors.

Correspondence

Xiaohong Tian. College of Natural Resources and Environment, Northwest A& F University, No.3 Taicheng Road, Yangling 712100, Shaanxi, China.

E-mail addresses: txhong@hotmail.com, txhong@nwsuaf.edu.cn (X. Tian).

Running title

Acknowledgements

We gratefully acknowledge financial support for this research from the National Key R&D Program (2016YFD0200308), and the Key R&D Program of Shaanxi (2019ZDLNY01-05-01), the Key Technologies R&D Program of China during the 12th Five-Year Plan period (2012BAD14B11).

Abstract

Knowledge about the changes in soil organic carbon (SOC) stocks and grain yields under different tillage and straw management is necessary to assess the feasibility and sustainability of conservation agriculture. An 8-year experiment was conducted in an intensive wheat (*Triticum aestivum* L.)–maize (*Zea mays* L.) rotation system in the southern Loess Plateau of China. Three tillage methods [control with no-tillage and straw removal (CK), no-tillage with straw stubbles 30–40 cm in height (NT), and rotary tillage with straw incorporation (RT)] were applied before maize planting, and two straw treatments [straw return (SR) and no straw return (SR0)] were applied after maize harvest. Thus, the treatments included CK-SR, CK-SR0, NT-SR, NT-SR0, RT-SR, and RT-SR0. Over 8 years, the SOC stock exhibited similar dynamic trends in all treatments, but was higher in NT, RT, and SR plots than in CK-SR0 plots. Compared with the initial soil, the SOC stock increased largest (34.1%) in NT-SR. Compared with the CK-SR0, the NT-SR, RT-SR, CK-SR, NT-SR0 and RT-SR0 increased the wheat grain yield by 47.2%, 36.8%, 24.9%, 25.1%, and 20.0%, respectively. The NT, RT and SR increased crop yield stability with the highest sustainable yield index in NT-SR for both wheat (0.67) and maize (0.70). This study showed the NT-SR was the best strategy for improving SOC stocks, grain yields and agricultural sustainability for the wheat-maize rotation system in northwestern China and other areas with similar climates and cropping systems.

KEYWORDS

Wheat-maize rotation,Straw return,No-tillage, Soil organic carbon, Agricultural sustainability

1 | INTRODUCTION

Soil degradationis a major impediment to global crop productionandimproper management in arable land is the main driver of land degradation (Ye&Van Ranst, 2011;Sampietro et al., 2018; Lorenz et al., 2019). With drier climates and increasing pressure on resources, land degradation has become a major issue that continues to negatively affect human and natural ecosystems in some parts of the world (Guillaume et al., 2016; Djuma et al., 2020).Continuing degradation in arable soils results indeclines insoil organic carbon(SOC) stocks, crop productivity, and ecosystem service values of increasing agricultural systems (Ma et al., 2020;Raimondo et al., 2020). TheSOCdepletion is also acknowledged as a major source of greenhouse gas emissions, resulting further in losses of soil fertility and ecosystem stability (Amundson et al., 2015; Rüegget al., 2019).Even small changes inthe SOC caused by anthropogenic disturbance in terrestrial ecosystems can profoundly affect the atmospheric C dioxide(CO_2)and thus get feedback to climate changes (Sayer et al., 2011). In recent years, increasingattentionshave been paid to SOC sequestration by optimizing appropriate crop rotation, integrated soil fertility management, and conservation tillage including crop residue management in agricultural ecosystems (Xia et al., 2018; Gonçalves et al., 2019; Berhane et al., 2020;Ryan et al., 2020; Sun et al., 2020).Therefore, understanding the SOC dynamics and the role that the soil plays in sequestering more atmospheric CO_2into soils are of incredible concern due to their great potential for both climate change mitigation and agricultural sustainability (Zhao et al., 2018a; Feng et al., 2020).

With a straw yield of 703.3 million tons (Mt) in 2014, and an average annual straw increase of 4% over the decades, China has become one of the most abundant countries in terms of straw resources (Hong et al., 2016; Yin et al., 2018). However, the agricultural soils in China have a relatively low SOC level due to the long cultivation history, highly intensive field management, and lower straw-return rates caused by large amounts of straw used as fuel and animal feeds or were burnt in fields (Zhao et al., 2018a;Hou et al., 2019; Berhane et al., 2020). Since crop residue contains large amounts of nitrogen (N), phosphorus (P), and potassium (K), adopting straw-return management practices in farmland facilitates the maintenance of soil nutrient balance and soil quality, and boosts the sustainability of agricultural production (Yin et al., 2018; Guan et al., 2020). As the largest producer and consumer of mineral fertilizers, China has consumed approximately 35% of the global mineral fertilizers for agricultural production (Sun et al., 2012; Yin et al., 2018). The application of mineral fertilizers with low levels of straw-return generally enhances grain yields in the short term, but exacerbates soil organic matter (SOM) depletion, deteriorates soil nutrient availability, resulting in the decline of agricultural sustainability in the long term (Gaffney et al., 2019). Conversely, straw return significantly enhanced SOC contents (14.9%) and crop yields (5.1%) with the same amounts of mineral-N applied in comparison with straw removal in global agro-ecosystems (Xia et al., 2018). Likewise, Zhao et al. (2018a) have reported an increase of 140 kg C $ha^{-1}yr^{-1}$ SOC stock from 1980 to 2011 in China's croplands (0-20 cm), and that approximately 40% of the incremental increase could be accounted for by straw return. However, it remains uncertainty that how agricultural soils respond to straw return (Liu et al., 2014; Berhane et al., 2020). For instance, Liu et al. (2014) reported that SOC sequestration was enhanced under straw return during the first 3 years, but afterwards that effect gradually decreased over time. Some studies have also reported that the effects of straw return may be negligible or negative (Garcia-Orenes et al., 2009; Wang et al., 2011). The distinctions might be due to various ecological conditions, soil conditions, methods of disposing straw, straw-returned rate, and experimental duration (Liu et al., 2014).

Straw incorporation through conventional tillage, such as plowing tillage and rotary tillage, is a common and effective field management practice with a strong influence on soil fertility, soil physical and biological properties and crop yields (Yu et al., 2017; Liu et al., 2021). On the one hand, frequent adoption of conventional tillage destroys soil structural stability, decreases the water holding capacity of soils, worsens the biological characteristics, and nutrient reserve and supply (Wang et al., 2011; Xu et al., 2019; Nouri et al., 2019). However, increasing evidences from manipulative experiments (Zhao et al., 2019a; Li et al., 2019) and meta-analyses (Zhao et al., 2019b; Jat et al., 2020) have showed that adopting conservation agriculture (CA) could improve soil quality and agricultural sustainability. The CA mainly consists of various reduced and even no-tillage techniques with more than 30% of crop residue retained on soil surface, providing effective strategies for combating soil degradation (Liu et al., 2020). It has been reported that SOC contents of topsoil increased with years under CA for its superiority on the protection of soil structure and reduced rates of soil degradation (Somasundaram et al., 2017; Reeves et al., 2019). The effects of CA on grain yields are highly variable, varying from increase (Liu et al., 2018; Peng et al., 2020), neutral (Zhang et al., 2018) to decrease (Pittelkow et al., 2015; Fiorini et al., 2020).

The intensive wheat (*Triticum aestivum* L.)-maize (*Zea mays* L.) double cropping systemis the major agricultural practice in the southern Loess Plateau of northwest China (Deng et al., 2006; Liu et al., 2017). The growth periods for wheat from mid-October to early June of next year, and for maize were from mid-June to early October. The high intensity with short time interval between wheat and maize growth periods in this agricultural system have been widely reported (Li et al., 2019). To achieve high grain yields, the excessive uses of mineral fertilizers and tillage, especially the plowing and rotary tillage, are indispensable (Yang et al., 2017; Xu et al., 2019). Under favorable conditions of water and fertilizer, the intensive field managements stimulate the degradation of plant residues and SOM, and thus result in SOC loss (Liu et al., 2014; Guan et al., 2020). For a long time, straw burning was adopted by farmers after crop harvest, which did not only lead to a waste of biomass resources, but also gave rise to an excessive emissions of greenhouse gases, and even left these regions in a thick haze (Hou et al., 2019; Li et al., 2019). As such, adopting sustainable, cleaner field management practices (i.e., conservation tillage and straw return) is essential to promote SOC sequestration and grain yields, thus attaining economic and environmental sustainability in grain production (Zhao et al., 2018a).

Moreover, most studies relate to SOC sequestration and grain yields affected by both straw return and tillage in the intensive wheat-maize system have focused on the period after maize harvest (Tian et al., 2016; Kan et al., 2020), but did not consider the effects of both straw return and tillage management practices after wheat harvest. Although long-term straw return is clearly an effective field management practice for sequestering C in soils, and a linear relationship exists between SOC sequestration and grain yields (Liu et al., 2014; Zhao et al., 2018a; Xu et al., 2019), there is a paucity of information on the effects of both no-tillage before maize planting and maize straw return on SOC sequestration and its relationship with grain yields and yield stability in the intensive wheat-maize system. Therefore, the present study utilized a long-term field experiment initiated in 2008 and aimed to examine the combined effects of no-tillage before maize planting and maize straw return on SOC sequestration, grain yields, yield stability and agricultural sustainability. The information obtained can be used to optimize both no-tillage and straw return management practices, enhance crop production, and improve agricultural sustainability for the wheat-maize rotation system in dry sub-humid areas of northwestern China and other areas with similar climates and cropping systems.

2 | MATERIALS AND METHODS

2.1 | Study site

The experimental site is located in the city of Sanyuan, Shaanxi province, in the southern Loess Plateau (34deg36'N, 108deg52'E). This region has a sub-humid, warm-temperate continental monsoon climate with a mean annual temperature and mean annual precipitationof12.9degC and 527 mm, respectively. The soil is termed as Lou soil (manural loess soil) and classified as Eum-Orthic Anthrosol (Udic Haplustalf in the USDA system). The basic soil properties (0–20 cm depth) are shown in Table 1.

2.2 | Experimental treatments and field management

This field experiment began in 2008. The site had a long history (> 40 year) of wheat and maize double cropping rotation under the same managements before the study, and the typical rotation of wheat (cv. Mianyang 26) and maize (cv. Nonghua 50) was also chosen for this study. A randomized complete block design experiment using 12.5-m-wide and 56-m-long plots was managed over 8 years with four replicates. Three tillage methods [control with no-tillage and straw removal (CK), no-tillage with straw stubbles 30–40 cm in height (NT), and rotary tillage with straw incorporation (RT)] were applied before maize planting, and two straw treatments [straw return (SR) and no straw return (SR0)] were applied after maize harvest. Thus, there were totally 24 plots with four replicates for each treatment(CK-SR, CK-SR0, NT-SR, NT-SR0, RT-SR, and RT-SR0).Both wheat and maize were harvested using combine-harvesters.Wheat straw was manually removed from the farmland in CK, but was remained with straw stubbles 30–40 cm in height in NT, and was chopped into about 10 cm pieces and incorporated into the top 10 cm soil layer immediately after harvest with ˜ 2-3 times of rotary tillage in RT. Maize straw was chopped into about 10 cm pieces and incorporated into the top 20 cm soil layer immediately after harvest with ˜ 2-3 times of rotary tillage in SR, and was manually removed from theSR0 plots.

The wheat was sown at a rate of 210–225 kg $ha^{-1}yr^{-1}$ with a row spacing of 15 cm, and the maize was planted at a density of approximately 63,000 plants ha^{-1} yr^{-1} with a row and plant spacing of 60 and 25 cm, respectively. The basal fertilization rates were 120 kg N ha^{-1} yr^{-1} and 102 kg $P_2O_5ha^{-1}yr^{-1}$for wheat production, and were 67.5 kg N ha^{-1} yr^{-1} and 22.5 kg P_2O_5 $ha^{-1}yr^{-1}$for maize production, respectively. A rate of 120 kg N ha^{-1} yr^{-1} was also applied at the tasseling stage of maize. Urea and diammonium phosphate provided the required N and P_2O_5 in all treatments. Before sowing wheat, ˜ 2-3 times of rotary tillage were applied at a depth of 20 cm in all the plots for the convenience of wheat seeding. Irrigation and pesticide management practices were in keeping with local agronomic practices.

2.3 | Soil sampling and analysis

After maize harvest, twelve soil samples were randomly collected from the topsoil layer (0–20 cm) in each plot in October every year. The fresh soil samples from each plot were mixed as a composite sample, air-dried, finely ground, and sieved to pass through a 0.15 mm mesh. The SOC was determined using $K_2Cr_2O_7$–H_2SO_4digestion method (Bao, 2000), and the measurement of SOC stocks was based on a constant soil mass (Xu et al., 2019).

2.4 |Biomass sampling and analysis

The aboveground biomass including grain, straw, and stubble, were recorded from 2008 through 2016. At maturity, biomass samples of wheat and maize were manually collected in the center of each plot from two separate 10-m^2 areas (2 rows x 10 m) for maize, and from two separate 2-m^2 areas (1 m x 2 m) for wheat, respectively. After air-drying, portions of biomass samples were oven-dried at 65 for biomass determination.

The root biomass of wheat and maize were estimated by 22% and 23% of aboveground biomass, respectively (Kong et al., 2005). The plant-derived C content was 40% of both wheat and maize (Johnson et al., 2006).

Grain yield stability of wheat and maize was calculated for the treatments by the yield variability(YV%, Xu et al., 2019):

$$YV = \frac{Y_{\text{std}}}{Y_m} \quad (1)\backslash n$$

The sustainable yield index (SYI) of wheat and maize was evaluated for the treatments accounting for all the 8-years' grain yields (Ghosh et al., 2012):

$$SYI = \frac{Y_m - Y_{\text{std}}}{Y_{\max}} \quad (2)\backslash n$$

2.5 | Statistical analysis

Data were subjected to analysis of variance (ANOVA) using the windows-based SPSS program (SPSS v19.0).The impacts of tillage management, straw management, and annual variation on SOC contents, wheat grain yields, and maize grain yields were tested using three-way ANOVAs. The effects of tillage and straw managements on plant-derived biomass and carbon, SOC stock, yield variations of both wheat and maize, and sustainable yield index of both wheat and maize were analyzed using two-way ANOVAs. Multiple comparisons were made for determining significant effects of treatments using the least significant difference (LSD) test with $P < 0.05$. Simple correlation coefficients and regression equations were developed to evaluate the relationships between grain yields and SOC stocks.

3 | RESULTS

3.1 |Carbon inputs

Compared with the CK, the accumulative input of plant-derived biomass was significantly enhanced by 72.1% and 61.6% under NT and RT, respectively (Fig. 1a; Table S1; both$P < 0.001$). Straw return increased the accumulative input of plant-derived biomass by 90.3% under SR relative to the SR0 ($P < 0.001$). No-tillage interacted with straw return to influence the accumulative input of plant-derived biomass ($P < 0.001$). Compared with the CK, the NT and RT increased the accumulative input of plant-derived biomass by 57.5% and 46.4%, respectively, in SR plots, while increased it by 106.8% and 97.1%, respectively, in SR0 plots (all $P < 0.01$). Compared with the SR0, the SR promoted the accumulative input of plant-derived biomass by 80.7%, 76.5%, and 137.3% in NT, RT, and CK plots, respectively (all $P < 0.001$). Compared with the CK-SR0, the accumulative input of plant-derived biomass in RT-SR0, NT-SR0, CK-SR, RT-SR, and NT-SR gradually increased significantly by 97.1%, 106.8%, 137.3%, 247.8%, and 273.7%, respectively (all$P < 0.01$).

The accumulative input of plant-derived C exhibited a trend that similar to those of the accumulative inputs of plant-derived biomass (Fig. 1a). The higher inputs of plant-derived biomass resulted in higher inputs of plant-derived C ranging from 22.7 Mg ha^{-1} in CK-SR0 to 84.8 Mg ha^{-1} in NT-SR. The total proportions of plant-derived C inputs derived from stubble and root in CK-SR0 were 23.9% and 76.1%, respectively (Fig. 1b). In other treatments, the total proportions of plant-derived C inputs derived from straw, stubble, and root were 41.0-63.0%, 9.0-14.2%, and 28.0-44.8%, respectively.

3.2 |Soil organic carbon contents and stocks

Over the 8-yr study, the SOC contents showed similar dynamic changing trends in all treatments (Fig. 2a). Compared with the CK, the NT and RT increased SOC contents by 7.4% and 5.5%, respectively (Fig. 2b; Table 2; $P < 0.001$). The SOC content was 6.5% higher under SR than under SR0 ($P < 0.001$). However, there were no interaction effects of tillage and straw managements on SOC contents (Table 2; $P > 0.05$). The largest SOC contents were 13.15 g kg^{-1} (2015) in CK-SR, 12.25 g kg^{-1} (2012) in CK-SR0, 12.84 g kg^{-1}(2015) in RT-SR0, 13.65 kg^{-1} (2015) in RT-SR, 14.12 kg^{-1} (2016) in NT-SR, and 12.79 (2016) in NT-SR0, respectively (Fig. 2a). The average SOC content in NT-SR was 2.7% and 8.0% higher than in RT-SR and CK-SR, respectively. After the 8-yr study, SOC stock was enhanced by 10.5% and 9.6% under NT and RT, respectively, relative to the CK, and was higher by 9.5% under SR than under SR0 ($P < 0.01$; Table 3 & S1). No interaction effects of tillage and straw managements existed on SOC contents ($P > 0.05$). Soil organic C stocks increased by 34.1% in NT-SR, following by RT-SR (33.9%), CK-SR (22.3%), NT-SR0 (21.3%), RT-SR0 (20.8%), and CK-SR0 (9.1%) compared to initial SOC stock in 2008 (Table 3).

3.3 | Grain yields

Compared with CK, the NT and RT increased wheat grain yield by 21.1% and 14.2%, respectively (Fig. 2a; Table 2; $P < 0.001$). Straw return increased wheat grain yields by 18.5% under SR relative to the SR0 ($P < 0.001$). Significant interactions between tillage and straw managements on wheat grain yields were detected ($P < 0.05$).In SR plots, the NT and RT increased wheat grain yields by 17.9% and 9.5, respectively, relative to the CK, while the increase of wheat grain yields in SR0 plots were up to 25.2% and 20.0% under NT and RT, respectively (all $P < 0.01$). Compared with the SR0, the SR increased wheat grain yields by 14.0%, 17.6%, and 24.9% under RT, NT, and CK, respectively (all$P < 0.01$). Compared with the CK-SR0, wheat grain yields significantly increased by 47.2%, 36.8%, 25.1%, 24.9%, and 20.0% in NT-SR, RT-SR, NT-SR0, CK-SR, and RT-SR0, respectively (Fig. 2b; $P < 0.01$).

Similar trends existed for maize grain yields with wheat grain yields in different treatments (Fig. 3a˜d). In most rotation cycle, grain yields of both wheat and maize in CK-SR were higher than in CK-SR0, except for wheat grain yields in 2011. In 2011–2013 and 2015-2016, wheat grain yields decreased under all treatments, but maize grain yields increased and then decreased substantially under all treatments. However, during 2013-2014, wheat grain yields increased substantially under all treatments. In 2012, all treatments reached their highest maize grain yields: 9.21, 8.52, 8.18, 8.17, 7.91, and 7.53 Mg ha^{-1} in NT-SR, RT-SR, NT-SR0, RT-SR0, CK-SR, and CK-SR0, respectively. However, the highest wheat grain yields of CK-SR0, NT-SR0 and RT-SR were 6.11, 7.40 and 8.21 Mg ha^{-1} in 2011, 6.97 and 7.18 Mg ha^{-1}for RT-SR0 and CK-SR in 2014, and 8.42 Mg ha^{-1} for NT-SR, respectively.

3.4 | Grain yield stability and sustainable yield index

The yield variations of wheat and maize were 25.1-28.6% and 13.8-18.6%, respectively (Fig. 4a). The yield variation of wheat was significant reduced by 8.3% under SR than under SR0 (Fig. 4a; Table S1;$P < 0.01$), while were not affected by tillage managements and its interaction with straw return ($P > 0.05$). Compared with the CK, yield variation of maize was significant lower by 24.4% and 22.6% under NT and RT, respectively ($P < 0.01$), while were not affected by straw return and its interaction with tillage managements ($P > 0.05$).

The sustainable yield index for wheat and maize were 0.47˜0.67 and 0.53˜0.70, respectively (Fig. 4b).Compared with the CK, the sustainable yield index was 19.9% and 13.2% higher for wheat, and were 17.1% and 8.9% higher for maize under NT and RT, respectively (Fig. 4b; Table S1; $P < 0.01$). The sustainable yield index of wheat and maize were 19.3% and 11.2% higher under SR than under SR0 ($P < 0.01$). No interactive effects of straw return and tillage managements on the sustainable yield index of both wheat and maize were found. Compared with CK-SR, the sustainable yield index was increased by 16.7% and 10.7% for wheat, and by 15.4% and 6.6% for maize in NT-SR and RT-SR, respectively. Those results indicated that combining NT with SR can improve the sustainable yield index of both wheat and maize.

3.5 | Relationship between SOCstocks and grain yields

Pearson correlation analysis for grain yields of both wheat and maize showed significant ($P< 0.01$) and positive correlations with SOC stocks (Fig. 5).

4 | DISCUSSIONS

4.1 |Responses ofSOC stocks and grain yields to tillage

Results of the 8-yr study significantly enhanced SOC stocks under no-tillage with wheat straw stubbles 30–40 cm in height in the long term. This observation is consistent with the previous studies reporting that long-term no-tillage increases SOC stocks when crop residue retained in fields (Somasundaram et al., 2017; Gonçalves et al., 2019; Liu et al., 2020). In general, reduction of soil disturbance is one of main reason underlying the enhanced potential of SOC sequestration under adopting conservation agriculture (Kan et al., 2020; Sun et al., 2020). No-tillage with straw retention protects aggregate-associated SOC from microbial attack, thus reducing SOC mineralization and increasing SOC stocks (Kan et al., 2020; Wang et al., 2020).

The 8-yr results revealed that no-tillage with wheat straw stubbles 30–40 cm in height increased grain yields of both wheat and maize compared with those in CK and RT. Previous studies have also reported positive responses of grain yields to no-tillage. For instance, Xu et al. (2019) and Peng et al. (2020) reported that long-term no-tillage can achieve significant improvements in grain yield over conventional tillage. However, numerous studies have reported that grain yields under no-tillage remained unchanged or even decreased (Pittelkow et al., 2015; Fiorini et al., 2020). Zhang et al. (2018) also reported that on average 6.9% decrease was observed in wheat yield under continuous no-tillage on a sandy loam soil in the North China Plain. Yield improvement in the present study resulted mainly from large amounts of stored SOC in NT. Previous studies have also demonstrated that no-tillage can enhance grain yields depending on many external factors, such as soil type, soil fertility, crop rotation, irrigation condition, and meteorological factors (Boomsma et al., 2010; Sun et al., 2020). Changes in site-specific characteristics and management as well as variations in climate might account for variations in grain yields including the dramatic decline of wheat grain yields in 2013.

4.2 | Responses of SOCstocks and grain yields to long-term straw return

Many studies have shown that straw return is an environmentally friendly and effective strategy to stabilize soil structure, improve soil fertility and sequester atmospheric CO_2 into agricultural soils (Zhao et al., 2018b; Guan et al., 2020; Xue et al., 2020). Our results indicate that long-term (8-yr) straw return significantly enhanced SOC stocks compared with CK-SR0 or even SOC levels in 2008, where SOC improvement was probably associated with the amount of plant-derived C inputs, as suggested previously (Liu et al., 2014; Ghosh et al., 2012; Berhane et al., 2020). The SOC levels in NT-SR and RT-SR differed significantly from those in CK-SR, NT-SR0, RT-SR0, and CK-SR0 in 2016, and SOC stocks increased as more plant-derived C inputs increased (Li et al., 2016), thereby effectively mitigating SOC loss from agricultural ecosystems due to intensive cropping and anthropogenic disturbance. In the present study, the SOC levels could be maintained without straw retention. This could be due to the higher conversion efficiency of plant-derived C to SOC from roots than straw (Ghafoor et al., 2017). Root-derived C inputs had been demonstrated as one of main C source for SOC maintenance (Zhao et al., 2018a). High crop productivity implied greater plant-derived C inputs, especially from belowground roots, thus resulting in additional C sequestration in agricultural soils (Liu et al., 2014). However, results of Li et al. (2016) and Zhao et al. (2018b) showed that SOC levels could not be maintained under straw removals of both wheat and maize in the same cropping system and region. This discrepancy might be due to soil depth and experimental duration. Thus, the effect of roots' persistence on SOC sequestration needs further confirmation and investigation to evaluate the efficiency of C sequestration and on roots' persistence for their contribution to SOC than straw under varied soil types, soil depth, experimental duration and climate conditions (Sukhdev et al., 2011; Liu et al., 2014).

The results of our field experiment indicate that grain yields of both wheat and maize increased under straw return compared with CK-SR0 and showed significant correlations with SOC stocks. Similar results were reported by Xu et al. (2019) based on an 11-yr field experiment in the Northern China Plain (NCP). Karami et al. (2012) and Wang et al. (2018) reported the positive effects of straw return on grain yields due mainly to improvements in the stability and strength of soil aggregates, the levels of soil nutrient and moisture, the activities of soil enzyme, thus providing a favorable physical, chemical and biological soil environment. However, a significant non-linear relationship was also reported between relative grain yields and topsoil SOC stocks (Lal, 2009), indicating no additional benefit from SOC sequestration on grain yields when SOC stocks have reached a critical value (Loveland and Webb, 2003; Krull et al., 2004). The positive correlation between grain yields and SOC stocks in the present study suggested that SOC stocks have not yet reached saturation and can be further enhanced by adopting appropriate field management practices.

4.3 |Responses of grain yield stability totillage and straw return

During the 8-yr periods, tillage systems significantly affected seasonal grain yields of both wheat and maize ($P < 0.01$, Table 1), which significantly correlated with SOC stocks. The SOC increases in NT-SR highlighted that the wheat-maize double cropping systemcan transform agricultural soils from net sources to net sinks of atmospheric CO_2 without reducing crop yields. Increased SOC stocks has potential positive feedback effects on soil fertility, water retention, biological functions and productivity (Zhang et al., 2018; Zhao et al., 2019a & b; Feng et al., 2020). However, more than 90% of plant-derived C under straw return could not be sequestrated by soils (Fig. 1; Table 2; Li et al., 2019). Thus, the improvement in tillage and straw management practices has improved grain yields in intensive wheat-maize double cropping system. Inter-annual variability in temperature and precipitation contributed to the year-to-year variability in grain yields (Najafi et al., 2019). Long-term field experiments provide valuable information regarding whether it is feasible to adopt no-tillage and straw return with agricultural sustainability in an intensive cropping system and address the challenges of achieving high grain yields economically and environmentally sustainable.

Yield variability was used as a negative measure of yield stability during the studied periods. Increasing evidences from manipulative experiments (Boomsma et al., 2010; Zhang et al., 2018) and meta-analyses(Huang et al., 2015; Sun et al., 2020) have documented that the response of grain yields to tillage and straw management practices is quite variable. Due to the difficulty of characterizing the response of yield increase and stability to SOC stocks, whether high SOC stocks can improve yield stability is still in doubt (Zhang et al., 2016). The 8-yr results revealed that no-tillage with wheat straw stubbles 30–40 cm in height increased yield stability of both wheat and maize under maize straw return, likely because both straw return and no-tillage have increased SOC stocks. Soil organic C sequestration contributed to increasing and stabilizing grain yields of both wheat and maize in NT and RT more than CK, and with SR than SR0 over the 8-yr periods. However, higher SOC stock is not always accompanied by higher grain yield. Higher SOC stocks did not result in higher wheat grain yields for all treatments in 2013 in comparison with those in other years (Fig. 2 & 3). Increasing SOC stocks in agricultural soils with adaption of NT-SR might nonetheless contribute to improvements of both wheat and maize grain yields and reduce the uncertainty of grain production in China, which is without doubt a matter of concern for the nation with the largest population in the world (Zhang et al., 2016; Zhao et al., 2018). Higher SOC stocks and yield stability could result in higher agricultural sustainability as indicated by higher sustainable yield index under adoption of no-tillage and/or straw return compared with those under CK-SR0. Therefore, the above findings reinforce the importance of adopting no-tillage and/or straw return, especially the combination of no-tillage with wheat straw stubbles height of 30–40 cm and maize straw return (NT-SR), for increasing SOC stocks and sustaining grain yield stability.

4 | CONCLUSIONS

This study supports that no-tillage and straw return are essential for improving SOC stocks, grain yields and agricultural sustainability in the continuous wheat–maize cropping system in the southern Loess Plateau. Soil organic C stocks increased in NT, RT and straw return plots than in CK-SR0 plots with the highest(21.8%) in NT-SR. Straw return, NT, and RT increased grain yields of both wheat and maize, yield stability and sustainable yield index. Combination of conservation tillage (e.g., NT, RT) and maize straw return can substantially increase SOC stocks, yield stability and agricultural sustainability. Moreover, the combinations of no-tillage with wheat straw stubbles 30–40 cm in height and maize straw return was an effective strategy to obtain high SOC stocks, increase grain yields of both wheat and maize and resulted in the optimal agricultural sustainability.

CONFLICT OF INTEREST

The authors declare no conflicts of interest.

REFERENCES

Amundson, R., Berhe, A. A., Hopmans, J. W., Olson, C., Sztein, A. E., & Sparks, D. L. (2015). Soil and human security in the 21st century.*Science* , 348, 1261071–1261071. https://doi.org/10.1126/science. 1261071

Bao, S.D.(2000). In: Bao, S.D. (Ed.), Soil and Agricultural Chemistry Analysis. China Agriculture Press, Beijing, pp. 11–13.

Berhane, M., Xu, M., Liang, Z., Shi, J., Wei, G., Tian, X.(2020). Effects of long-term straw return on soil organic carbon storage and sequestration rate in North China upland crops: A meta-analysis. *Global Change Biology* ,26, 2686–2701. https://doi.org/10.1111/gcb.15018.

Boomsma, C.R., Santini, J.B., West, T.D., Brewer, J.C., McIntyre, L.M., Vyn, T.J.(2010). Maize grain yield responses to plant height variability resulting from crop rotation and tillage system in a long-term experiment. *Soil & Tillage Research* ,106, 227–240. https://doi.org/10.1016/j.still.2009.12.006.

Deng, X.P., Shan, L., Zhang, H.P., Turner, N.C.(2006). Improving agricultural water use efficiency in arid and semiarid areas of China.*Agricultural Water Management* , 80, 23–40. https://doi.org/10.1016/j.agwat.2005.07.021.

Djuma, H., Bruggeman, A., Zissimos, A., Christoforou, I., Eliades, M., &Zoumides, C. (2020). The effect of agricultural abandonment and mountain terrace degradation on soil organic carbon in a Mediterranean landscape. *Catena* , 195, 104741. https://doi.org/10.1016/j.catena.2020.104741.

Feng, Q., An, C., Chen, Z., Wang, Z.(2020). Can deep tillage enhance carbon sequestration in soils? A meta-analysis towards GHG mitigation and sustainable agricultural management. *Renewable &Sustainable Energy Reviews* , 133, 110293. https://doi.org/10.1016/j.rser.2020.110293.

Fiorini, A., Boselli, R., Maris, S.C., Santelli, S., Ardenti, F., Capra, F., Tabaglio, V.(2020). May conservation tillage enhance soil C and N accumulation without decreasing yield in intensive irrigated croplands? Results from an eight-year maize monoculture. *Agriculture, Ecosystems & Environment* , 296, 106926. https://doi.org/10.1016/j.agee.2020.106926.

Gaffney, J., Bing, J., Byrne, P.F., Cassman, K.G., Ciampitti, I., Delmer, D., Habben, J., Lafitte, H.R., Lidstrom, U.E., Porter, D.O., Sawyer, J.E., Schussler, J., Setter, T., Sharp, R.E., Vyn, T.J., Warner, D.(2019). Science-based intensive agriculture: Sustainability, food security, and the role of technology. *Global Food Security* ,23, 236–244. https://doi.org/10.1016/j.gfs.2019.08.003.

García-Orenes, F., Cerdà, A., Mataix-Solera, J., Guerrero, C., Bodí, M. B., Arcenegui, V., Zornoza, R., Sempere, J. G.(2009). Effects of agricultural management on surface soil properties and soil-water losses in eastern Spain. *Soil & Tillage Research* , 106, 117–123. https://doi.org/10.1016/j.still.2009.06.002.

Ghafoor, A., Poeplau, C., Kätterer, T.(2017). Fate of straw- and root-derived carbon in a Swedish agricultural soil. *Biology &Fertility of Soils.* 53, 257–267. https://doi.org/10.1007/s00374-016-1168-7.

Ghosh, S., Wilson, B., Ghoshal, S., Senapati, N., Mandal, B.(2012). Organic amendments influence soil quality and carbon sequestration in the Indo Gangetic plains of India. *Agriculture, Ecosystems & Environment* ,156, 134–141. https://doi.org/10.1016/j.agee.2012.05.009.

Gonçalves, D.R.P., Sá, João C.M., Mishra, U., Fornari, A.J., Furlan, F.J.F., Ferreira, L.A., Inagaki, T.M., Romaniw, J., de Oliveira F.A., Briedis, C.(2019). Conservation agriculture based on diversified and high-performance production system leads to soil carbon sequestration in subtropical environments.*Journal of Cleaner Production* , 219, 136–147. https://doi.org/10.1016/j.jclepro.2019.01.263.

Guan, X., Wei, L., Turner, N.C., Ma, S., Yang, M., Wang, T.(2020). Improved straw management practices promote in situ straw decomposition and nutrient release, and increase crop production. *Journal of Cleaner Production* ,250, 119514. https://doi.org/10.1016/j.jclepro.2019.119514.

Guillaume, T., Holtkamp, A. M., Damris, M., Brümmer, B., &Kuzyakov, Y. (2016). Soil degradation in oil palm and rubber plantations under land resource scarcity.*Agriculture, Ecosystems & Environment,* 232, 110-118. http://dx.doi.org/10.1016/j.agee.2016.07.002.

Hong, J., Ren, L., Hong, J., Xu, C.(2016). Environmental impact assessment of corn straw utilization in China. *Journal of Cleaner Production* , 112,1700–1708. http://dx.doi.org/10.1016/j.jclepro.2015.02.081.

Hou, L., Keske, C., Hoag, D., Balezentis, T., Wang, X.(2019). Abatement costs of emissions from burning maize straw in major maize regions of China: Balancing food security with the environment. *Journal of Cleaner Production* , 208, 178–187. https://doi.org/10.1016/j.jclepro.2018.10.047.

Huang, M., Zhou, X., Cao, F., Xia, B., Zou, Y.(2015). No-tillage effect on rice yield in China: A meta-analysis.*Field Crops Research* , 183, 126–137. http://dx.doi.org/10.1016/j.fcr.2015.07.022.

Jat, M.L., Chakraborty, D., Ladha, J.K., Rana, D.S., Gathala, M.K., McDonald, A., Gerard, B.(2020). Conservation agriculture for sustainable intensification in South Asia. *Nature Sustainability* , 3(4), 336–343. https://doi.org/10.1038/s41893-020-0500-2.

Johnson, J.M.F., Allmaras, R.R., Reicosky, D.C.(2006). Estimating source carbon from crop residues, roots and rhizodeposits using the national grain-yield database. *Agronomy Journal* , 98, 622–636. https://doi.org/10.2134/agronj2005.0179.

Kan, Z., Ma, S., Liu, Q., Liu, B., Virk, A.L., Qi, J., Zhao, X., Lal, R., Zhang, H.(2020). Carbon sequestration and mineralization in soil aggregates under long-term conservation tillage in the North China Plain. *Catena* ,188, 104428. https://doi.org/10.1016/j.catena.2019.104428.

Karami, A., Homaee, M., Afzalinia, S., Ruhipour, H., Basirat, S.(2012). Organic resource management: impacts on soil aggregate stability and other soil physicochemical properties. *Agriculture, Ecosystems & Environment* , 148, 22–28. https://doi.org/10.1016/j.agee.2011.10.021.

Kong, A.Y.Y., Six, J., Bryant, D.C., Denison, R.F., van Kessel, C.(2005). The relationship between carbon input, aggregation, and soil organic carbon stabilization in sustainable cropping systems. *Soil Science Society of America Journal* , 69, 1078–1085. https://doi.org/10.2136/sssaj2004.0215.

Krull, E.S., Skjemstad, J.O., Baldock, J.A.(2004). Functions of Soil Organic Matter and the Effect on Soil Properties. Grains Research and Development Corporation (GRDC).

Li, S., Li, X., Zhu, W., Chen, J., Tian, X., Shi, J.(2019). Does straw return strategy influence soil carbon sequestration and labile fractions? *Agronomy Journal* ,111(2), 897–906. https://doi.org/10.2134/agronj2018.08.0484.

Liu, C., Lu, M., Cui, J., Li, B., Fang, C.(2014). Effects of straw carbon input on carbon dynamics in agricultural soils: a meta-analysis.*Global Change Biology* , 20 (62), 1366–1381. https://doi.org/10.1111/gcb.12517.

Liu, N., Liu, N., Li, Y., Cong, P., Wang, J., Guo, W., Pang, H., Zhang, L.(2021). Depth of straw incorporation significantly alters crop yield, soil organic carbon and total nitrogen in the North China Plain.*Soil & Tillage Research* ,205, 104772. https://doi.org/10.1016/j.still.2020.104772.

Liu, S., Zhang, X., Liang, A., Zhang, J., Müller, C., Cai, Z.(2018). Ridge tillage is likely better than no tillage for 14-year field experiment in black soils: Insights from a ^{15}N-tracing study. *Soil & Tillage Research* , 179, 38–46. https://doi.org/10.1016/j.still.2018.01.011.

Liu, Z., Chen, Z., Ma, P., Meng, Y., Zhou, J.(2017). Effects of tillage, mulching and N management on yield, water productivity, N uptake and residual soil nitrate in a long-term wheat-summer maize cropping system.*Field Crops Research* ,213, 154–164. http://dx.doi.org/10.1016/j.fcr.2017.08.006.

Liu, Z., Gao, T., Tian, S., Hu, H., Li, G., Ning, T.(2020). Soil organic carbon increment sources and crop yields under long-term conservation tillage practices in wheat-maize systems. *Land Degradation & Development* ,31(9), 1138–1150. https://doi.org/10.1002/ldr.3531.

Lorenz, K., Lal, R., & Ehlers, K. (2019). Soil organic carbon stock as an indicator for monitoring land and soil degradation in relation to United Nations' Sustainable Development Goals.*Land Degradation & Development,* 30, 824–838. https://doi.org/10.1002/ldr.3270.

Loveland, P., Webb, J.(2003). Is there a critical level of organic matter in the agricultural soils of temperate regions: a review.*Soil & Tillage Research* ,70, 1–18. https://doi.org/10.1016/S0167-1987(02)00139-3.

Ma, X., Zhang, X., & Tian, D. (2020). Farmland degradation caused by radial diffusion of CO_2 leakage from carbon capture and storage. *Journal of Cleaner Production,* 255, 120059. https://doi.org/10.1016/j.jclepro.2020.120059.

Najafi, E., Pal, I., Khanbilvardi, R.(2019). Climate drives variability and joint variability of global crop yields. *Science of the Total Environment* , 662, 361–372. https://doi.org/10.1016/j.scitotenv.2019.01.172.

Nouri, A., Lee, J., Yin, X., Saxton, A.M., Tyler, D.D., Sykes, V.R., Arelli, P.(2019). Crop species in no-tillage summer crop rotations affect soil quality and yield in an Alfisol. *Geoderma* , 345, 51–62. https://doi.org/10.1016/j.geoderma.2019.02.026.

Peng, Z., Wang, L., Xie, J., Li, L., Coulter, J. A., Zhang, R., Luo, Z., Cai, L., Carberrye, P., Whitbread, A.(2020). Conservation tillage increases yield and precipitation use efficiency of wheat on the semi-arid Loess Plateau of China. *Agricultural Water Management* , 231, 106024. https://doi.org/10.1016/j.agwat.2020.106024.

Pittelkow, C.M., Liang, X., Linquist, B.A., van Groenigen, K.J., Lee, J., Lundy, M.E., van Gestel, N., Six, J., Venterea, R.T., van Kessel, C.(2015). Productivity limits and potentials of the principles of conservation agriculture. *Nature* , 517, 365–368. https://doi.org/10.1038/nature13809.

Raimondo, M., Nazzaro, C., Marotta, G., & Caracciolo, F. (2020). Land degradation and climate change: Global impact on wheat yields.*Land Degradation & Development* , 32:387–398 http://dx.doi.org/10.1002/ldr.3699.

Reeves, S.H., Somasundaram, J., Wang, W.J., Heenan, M.A., Finn, D., Dalal, R.C.(2019). Effect of soil aggregate size and long-term contrasting tillage, stubble and nitrogen management regimes on CO_2 fluxes from a Vertisol. *Geoderma* , 337, 1086–1096. https://doi.org/10.1016/j.geoderma.2018.11.022.

Ryan, J.(2020). Soil fertility, crop nutrition, and cropping systems: Research for Mediterranean dryland agriculture. *Agronomy Journal* ,112(5), 3350–3360. https://doi.org/10.1002/agj2.20374.

Rüegg, J., Quezada, J. C., Santonja, M., Ghazoul, J., Kuzyakov, Y., Buttler, A., & Guillaume, T. (2019). Drivers of soil carbon stabilization in oil palm plantations. *Land Degradation & Development* , 30(16), 1904-1915. https://doi.org/10.1002/ldr.3380.

Sampietro V. M., Peña M. J. L., Roldán, J., Maldonado, M., Lefebvre, M., & Vattuone, M. (2018). Human-driven geomorphological processes and soil degradation in Northwest Argentina: A geoarchaeological view. *Land Degradation & Development* , 29(11), 3852-3865. https://doi.org/10.1002/ldr.3128.

Sayer, E.J., Heard, M.S., Grant, H.K., Marthews, T.R., Tanner, E.V.J.(2011). Soil carbon release enhanced by increased tropical forest litterfall. *Nature. Climate Change* ,1, 304–307. https://xs.scihub.ltd/https://doi.org/10.1038/nclimate1190.

Somasundaram, J., Reeves, S., Wang, W., Heenan, M., Dalal, R.(2017). Impact of 47 years of no-tillage and stubble retention on soil aggregation and carbon distribution in a vertisol. *Land Degradation & Development* , 25, 1589–1602. https://doi.org/10.1002/ldr.2689.

StSukhdev, S.M., Marvin, N., Elston, D.S., Brian, M., Miles, D., Dick, P.(2011). Long-term straw management and N fertilizer rate effects on quantity and quality of organic C and N and some chemical properties in two contrasting soils in Western Canada. *Biology & Fertility of Soils* ,47, 785–800. https://doi.org/10.1007/s00374-011-0587-8.

Sun, B., Zhang, L., Yang, L., Zhang, F., Norse, D., Zhu, Z.(2012). Agricultural non-point source pollution in China: causes and mitigation measures. *AMBIO* , 41(4), 370–379. http://dx.doi.org/10.1007/s13280-012-0249-6.

Sun, W., Canadell, J.G., Yu, L., Yu, L., Zhang, W., Smith, P., Fischer, T., Huang, Y.(2020). Climate drives global soil carbon sequestration and crop yield changes under conservation agriculture. *Glob. Change Biol* ., 26, 3325–3335. https://doi.org/10.1111/gcb.15001.

Tian, S., Ning, T., Wang, Y., Liu, Z., Li., G., Li, Z., Lal, R.(2016). Crop yield and soil carbon responses to tillage method changes in North China. *Soil & Tillage Research* ,163, 207–213. https://doi.org/10.1016/j.still.2016.06.005.

Wang, H., Wang, S., Yu, Q., Zhang, Y., Wang, R., Li, J., Wang, X.(2020). No tillage increases soil organic carbon storage and decreases carbon dioxide emission in the crop residue-returned farming system. *Journal of Environmental Manage* ment, 261, 110261. https://doi.org/10.1016/j.jenvman.2020.110261.

Wang, J., Chen, Z., Chen, L., Zhu, A.(2011). Surface soil phosphorus and phosphatase activities affected by tillage and crop residue input amounts. *Plant Soil &Environ* ment, 57, 251–257. https://doi.org/10.17221/437/2010-PSE.

Wang, S., Zhang, Y., Ju, W., Chen, J., Ciais, P., Cescatti, A., Sardans, J., Janssens, I.A., Wu, M., Berry, J.A., Campbell, E., Fernández-Martínez, M., Alkama, R., Sitch, S., Friedlingstein, P., Smith, W.K., Yuan, W., He, W., Lombardozzi, D., Kautz, M., Zhu, D., Lienert, S., Kato, E., Poulter, B., Sanders, T.G.M., Krüger, I., Wang, R., Zeng, N., Tian, H., Vuichard, N., Jain, A.K., Wiltshire, A., Haverd, V., Goll, D.S., Peñuelas, J.(2020). Recent global decline of CO_2 fertilization effects on vegetation photosynthesis.*Science* , 370(6522), 1295–1300. https://doi.org/10.1126/science.abb7772.

Wang, X., Jia, Z., Liang, L., Zhao, Y., Yang, B., Ding, R., Wang, J., Nie, J.(2018). Changes in soil characteristics and maize yield under straw returning system in dryland farming. *Field Crops Research* , 218, 11-17. https://doi.org/10.1016/j.fcr.2017.12.003.

Xia, L., Lam, S.K., Wolf, B., Kiese, R., Chen, D., Butterbach-Bahl, K.(2018). Trade-offs between soil carbon sequestration and reactive nitrogen losses under straw return in global agroecosystems. *Global Change Biol* ogy, 24, 5919–5932. https://doi.org/10.1111/gcb.14466.

Xu, J., Han, H., Ning, T., Li, Z., Lal, R.(2019). Long-term effects of tillage and straw management on soil organic carbon, crop yield, and yield stability in a wheat-maize system. *Field Crops Research* , 233, 33–40. https://doi.org/10.1016/j.fcr.2018.12.016.

Xue, B., Huang, L., Huang, Y.N., Kubar, K.A., Li, X.K., Lu, J.W.(2020). Straw management influences the stabilization of organic carbon by Fe (oxyhydr)oxides in soil aggregates. *Geoderma* . https://doi.org/10.1016/j.geoderma.2019.113987.

Yang, X., Lu, Y., Ding, Y., Yin, X., Raza, S., Tong, Y.(2017). Optimising nitrogen fertilisation: A key to improving nitrogen-use efficiency and minimising nitrate leaching losses in an intensive wheat/maize rotation (2008–2014). *Field Crops Research* , 206, 1–10. http://dx.doi.org/10.1016/j.fcr.2017.02.016.

Ye, L., & Van Ranst, E. (2009). Production scenarios and the effect of soil degradation on long-term food security in China. *Global Environmental Change* , 19(4), 464-481. https://doi.org/10.1016/j.gloenvcha.2009.06.002.

Yin, H., Zhao, W., Li, T., Cheng, X., Liu, Q.(2018). Balancing straw returning and chemical fertilizers in China: Role of straw nutrient resources. *Renewable Sustainable Energy Rev* iews, 81, 2695–2702. https://doi.org/10.1016/j.rser.2017.06.076.

Yu, K., Dong, Q., Chen, H.., Feng, H., Zhao, Y., Si, B., Li, Y., Hopkins, D. W.(2017). Incorporation of pretreated straw improves soil aggregate stability and increases crop productivity.*AgronomyJournal* , 109(5), 2253–2265.https://doi.org/10.2134/agronj2016.11.0645.

Zhang, X., Sun, N., Wu, L., Xu, M., Bingham, I.J., Li, Z.(2016). Effects of enhancing soil organic carbon sequestration in the topsoil by fertilization on crop productivity and stability: Evidence from long-term experiments with wheat-maize cropping systems in China.*Science of the Total Environment* , 562, 247–259. http://dx.doi.org/10.1016/j.scitotenv.2016.03.193.

Zhang, X., Zhu, A., Xin, X., Yang, W., Zhang, J., Ding, S.(2018). Tillage and residue management for long-term wheat-maize cropping in the North China Plain: I. Crop yield and integrated soil fertility index.*Field Crops Research* , 221, 157–165. https://doi.org/10.1016/j.fcr.2018.02.025.

Zhao, S., Qiu, S., Xu, X., Ciampitti, I.A., Zhang, S., He, P.(2019a). Change in straw decomposition rate and soil microbial community composition after straw addition in different long-term fertilization soils. *Applied Soil Ecol* ogy, 138, 123–133. https://doi.org/10.1016/j.apsoil.2019.02.018.

Zhao, X., Liu, B., Liu, S., Qi, J., Wang, X., Pu, C., Li, S., Zhang, X., Yang, X., Lal, R., Chen, F., Zhang, H.(2019b). Sustaining crop production in China's cropland by crop residue retention: A meta-analysis. *Land Degradation & Development* , 31(6), 694–709. https://doi.org/10.1002/ldr.3492.

Zhao, Y., Wang, M., Hu, S., Zhang, X., Ouyang, Z., Zhang, G., Huang, B., Zhao, S., Wu, J., Xie, D., Zhu, B., Yu, D., Pan, X., Xu, S., Shi, X.(2018a). Economics- and policy-driven organic carbon input enhancement dominates soil organic carbon accumulation in Chinese croplands. *Proceeding of the National Academy of Sciences of the United States of America* , 115(16), 4045–4050. https://doi.org/10.1073/pnas.1700292114.

Zhao, H., Shar, A.G., Li, S., Chen, Y., Shi, J., Zhang, X., Tian, X.(2018b). Effect of straw return mode on soil aggregation and aggregate carbon content in an annual maize-wheat double cropping system.*Soil & Tillage Research* , 175, 178–186.http://dx.doi.org/10.1016/j.still.2017.09.012.

Tables

Table 1 Soil physicochemical properties at 0–20 cm depth in 2008.

Soil properties	Value
Sand (g kg^{-1})	271
Silt (g kg^{-1})	408
Clay (g kg^{-1})	321
Bulk density (g cm^{-3})	1.21
pH	8.20
Organic carbon (g kg^{-1})	11.32
Total nitrogen (g kg^{-1})	1.17
Total phosphorus (g kg^{-1})	0.85
Total potassium (g kg^{-1})	29.43
Available nitrogen (mg kg^{-1})	19.37
Available phosphorus (mg kg^{-1})	48.60
Available potassium (mg kg^{-1})	253.34

Table 2 Results (F -values) of two-way ANOVAs on the effects of tillage and straw management practices as well as their interactions on soil organic carbon (SOC), and grain yields of both wheat and maize between 2008 and 2016.

	SOC	Wheat grain yields	Maize grain yields
T	68.32***	130.47***	145.30***
S	149.82***	301.65***	181.94***
T×S	1.55	3.77*	2.18
Y	68.27***	370.23***	211.60***
Y×T	2.78**	3.86***	6.14***
Y×S	2.27*	7.03***	8.06***
Y×T×S	1.00	5.09***	2.93**

T, tillage management; S, straw management; Y, year. F -values and significance level with factors of straw management (df = 1), tillage management (df = 2) and year (df = 7). *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

Table 3 The changes in the mean of soil organic carbon stock between 2008 and 2016.

Treatment	Treatment	SOC (Mg ha^{-1})	SOC (Mg ha^{-1})	SOC (Mg ha^{-1})
Tillage	Straw	2008	2016	Difference
NT	SR	27.30 a	36.60 a	9.30 a
RT	SR	26.92 a	36.06 ab	9.14 a
CK	SR	27.71 a	33.91 b	6.19 b
NT	SR0	27.83 a	33.76 b	5.94 b
RT	SR0	27.96 a	33.76 b	5.80 b
CK	SR0	27.30 a	29.78 c	2.48 c

CK, control with no-tillage and straw removal before maize planting; NT, no-tillage with straw stubbles 30–40 cm in height before maize planting; RT, rotary tillage with straw incorporation before maize planting; SR, straw return after maize harvest; SR0, no straw return after maize harvest. Values followed by different lowercase letters within the same column indicate significant difference at $P < 0.05$.

Figure caption

Fig. 1. Accumulative plant-derived biomass and C affected by different tillage and straw management practices during 8 years. CK, control with no-tillage and straw removal before maize planting; NT, no-tillage with straw stubbles 30–40 cm in height before maize planting; RT, rotary tillage with straw incorporation before maize planting; SR, straw return after maize harvest; SR0, no straw return after maize harvest. Different letters on the bar indicate significant different at the 5% level. The same below.

Fig.2. Change in soil organic carbon (SOC, 0–20 cm, a) and the corresponding mean value (b) of different treatments during 8 years.

Fig.3. Changes in wheat (a, b) and maize (c, d) grain yields in different treatments during 8 yr.

Fig.4. Yield variation (%, a) and sustainable yield index (b) of wheat and maize for different treatments during 2009-2016.

Fig. 5. Relationship between grain yields and soil organic carbon (SOC) stocks in the 0–20 cm soil layer under different treatments.

Fig. 1.

Hosted file

image1.emf available at https://authorea.com/users/424675/articles/529704-increasing-soil-organic-carbon-sequestration-and-yield-stability-simultaneously-through-combined-no-tillage-and-straw-return-in-wheat-maize-rotation

Fig. 2.

Hosted file

image2.emf available at https://authorea.com/users/424675/articles/529704-increasing-soil-organic-carbon-sequestration-and-yield-stability-simultaneously-through-combined-no-tillage-and-straw-return-in-wheat-maize-rotation

Fig. 3.

Hosted file

image3.emf available at https://authorea.com/users/424675/articles/529704-increasing-soil-organic-carbon-sequestration-and-yield-stability-simultaneously-through-combined-no-tillage-and-straw-return-in-wheat-maize-rotation

Fig. 4.

Hosted file

image4.emf available at https://authorea.com/users/424675/articles/529704-increasing-soil-organic-carbon-sequestration-and-yield-stability-simultaneously-through-combined-no-tillage-and-straw-return-in-wheat-maize-rotation

Fig. 5.

Hosted file

image5.emf available at https://authorea.com/users/424675/articles/529704-increasing-soil-organic-carbon-sequestration-and-yield-stability-simultaneously-through-combined-no-tillage-and-straw-return-in-wheat-maize-rotation

Supplementary Materials

Table S1 Results (F -values) of two-way ANOVAs on the effects of tillage and straw management practices as well as their interactions on plant-derived biomass (Plant-B), plant-derived carbon (Plant-C), soil organic carbon stock (SOC stock), yield variations of wheat (YV_w), yield variations of maize (YV_m), sustainable yield index of wheat (SYI_w), and sustainable yield index of maize (SYI_m).

	Plant-B	Plant-C	SOC stock	YV_w	YV_m	SYI_w	SYI_m
S	15460.4***	15460.4***	23.75***	10.20***	0.01	334.68***	160.43***
T	3867.2***	3867.2***	11.44***	1.24	12.99***	119.65***	117.50***
S×T	49.0***	49.0***	0.74	1.25	1.40	0.75	1.32

S, straw management; T, tillage management. F -values and significance level with factors of straw management (df = 1) and tillage management (df = 2). ***$p < 0.001$.